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Accounting for the short term substitution effects of walking and cycling in sustainable transportation

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Abstract

The environmental benefits of bicycling and walking depend on the degree to which their use substitutes for car driving. Assuming that every walking and bicycling trip replaces a driving trip is likely to produce overestimates of the potential for such modes to reduce vehicle travel and city-scale greenhouse gas emissions. Measuring this "substitution effect" is not straightforward. There are many dimensions of the substitution effect, including trip type, substituting mode, extent, time horizon, and activity patterns. Previously used approaches to measure substitution include indirect inference and direct questioning. This study piloted an intercept survey using the direct questioning approach at five locations in two metropolitan areas. The rate at which utilitarian walking or cycling trips substituted for auto trips ranged between 25% and 86%. Logistic regression models demonstrate that disparate factors explain walking substitution and bicycling substitution behavior; age is significantly correlated with substitutive walking behavior while number of car trips per week and helmet use are each significant predictors of bicycle substitution. This research represents a valuable first step toward developing a method to estimate the substitution effect that is useful for practitioners. Better estimates of the substitution effect will in turn lead to better estimates of the environmental impacts of bicycling and walking.

Introduction

Proponents of walking and bicycling – active modes of transportation – commonly cite benefits to both personal health and the environment. While any level of walking or bicycling produces health benefits, the environmental benefits, such as reduced pollution and greenhouse gas emissions, depend in large part on the degree to which active travel (AT) substitutes for vehicular trips. The value of AT as a strategy for addressing environmental problems comes from its potential as an alternative to driving, the primary source of environmental problems stemming from the transportation sector. Thus, simply measuring the number of bicycling and walking trips or the share of trips by these modes is insufficient to estimate their potential environmental benefits. Accurately assessing potential AT benefits requires efforts to assess the degree and nature of substitution. Such an assessment will help cities evaluate the extent to which the promotion of AT mitigates greenhouse gas emissions (GHGs) and provides other environmental benefits.

The assumption that walking and bicycling substitutes for driving often does not apply. For instance, AT for recreational purposes, such as taking a stroll around the neighborhood, comprises trips taken for their own sake rather than as an alternative to auto trips. In other cases, AT might constitute additional utilitarian travel rather than replacing driving. One example is when a resident decides to walk to the grocery store, in part motivated by the desire to achieve some exercise on a nice day, but otherwise would have simply waited until his or her next driving trip to the store. This walk trip is an *extra* trip, rather than a replacement (or substitution) trip. Thus, it is inappropriate to assume a one-to-one match between AT trips made and driving trips not made, as this assumption could either over-estimate (if not every AT trip replaces a driving trip) or under-estimate (if AT trips sometimes replace more than one driving trip) actual substitution. In addition, the length of the AT trip could be shorter (or possibly longer) than the driving trip it replaces, in which case it is also inappropriate to assume a one-to-one match between miles by walking and bicycling and miles by car.

This research effort focuses on the ability of AT to substitute for utilitarian auto travel. While recreational driving is a popular past time (particularly in the United States (**NSRE, 2002**), such travel is predominantly associated with long-distance scenic drives and visiting national parks (**Hallo and Manning, 2009**). In contrast, the claimed significance of AT substitution is based on local or city-scale congestion and GHG-reduction potential. Identifying which AT trips substitute for utilitarian automobile trips and measuring how much driving is reduced as a result are critical steps to accurately assessing the city-scale environmental implications of walking and bicycling.

In this paper we first present a conceptual framework to understand substitution behavior in terms of its key dimensions: trip types, mode types, frequency of behaviors, time horizon, and activity patterns. Second, we review previous approaches to estimating and measuring the substitution effect in light of these dimensions. Third, we describe the methodology and results of a five-city pilot test of an intercept survey aimed to quantify trip-specific AT substitution. Finally, we present the results of the intercept survey, including two logistic regression models to estimate factors associated with auto substitution among walkers and bicyclists. Our approach employs direct questioning through intercept surveys as a basis for quantifying AT substitution for a specific trip. We discuss the applicability of intercept surveys and offer methodological recommendations for future study.

Conceptual framework

AT substitution for vehicular travel takes many forms and plays out in complex ways. This section seeks to provide a clear conceptual framework for the various dimensions of substitution and describes their relation to broader aspects of travel. Typical "four-step" travel demand modeling suggests that travelers decide to make a trip and select a destination prior to choosing a mode. But, individuals who regularly walk or bicycle often reverse these steps. Their desire to walk or bicycle may lead them to make a trip in the first place, or they may consider a different set of destinations than if they were to drive—not only closer destinations but also those for which walking and bicycling are safer, more comfortable, and more attractive—all qualities that are not accounted for in traditional destination choice models.

Furthermore, mode choice may lead to differences in choosing a single destination, but also in forming "trip chains" of stops at multiple destinations. Changes in mode, destination, and frequency may impact the type and frequency of activities one engages in, which in turn can lead to changes in VMT. An individual might cycle to the local market, then the pharmacy, and then coffee shop instead of driving to the large grocery store containing all those services in one destination. The same individual might then forego an auto trip to the gym, deciding he has gotten enough daily exercise through utilitarian cycling. In other words, mode substitution might go hand-in-hand with destination and even activity substitution.

Substituting a specific trip may be one component in a behavior change process that in turn leads to longer term substitution behaviors, possibly culminating in a decision to give up auto use entirely. An individual might choose to live in an AT-friendly neighborhood, forego auto-ownership, and rely entirely on walking and bicycling. In this case, daily AT use that does not qualify as trip-specific substitution could still be considered long-term, or lifestyle, substitution. These examples illustrate the inherent complexity in this issue. We identify five important dimensions of substitution behavior.

Trip type (or trip purpose)

Previous studies tend to focus on the ability of specific modes to substitute each other for certain trip types – such as commute trips, non-work trips, and recreational trips – though few have quantified the degree of substitution. Several studies focus on non-work travel (**Handy and Yantis, 1997; Handy and Clifton, 2001; Krizek et al., 2009a**). It is likely that different types of trips (e.g., work versus non-work, commutes to work versus travel to meetings) have different potentials for substitution.

Substituting mode

Many travel modes could potentially substitute for driving. The potential to substitute depends on the modes available to a particular individual for a particular trip; available modes are a function of both individual characteristics (e.g., auto ownership, bicycling ability) and the trip characteristics (e.g., distance to destination, presence of bike lanes along the route). Walking is a possible substitute for the shortest trips, bicycling for middle-range trips, and transit for longer-range trips, though the viable distances for each mode will vary, and many trips will have two or more possible substitutes. Note that substitution for other pairs of modes could also occur. (e.g., transit trips substituting for bicycling trips, or vice versa.)

Extent

Another consideration is the extent of substitution in terms of both trip frequency and trip length. A commuter cycling to work daily is likely to have a greater impact on a city's transportation system than someone bicycling to the corner store once per month. Both the frequency and the distance of the trip made can differ from the trip replaced. Destination substitution may go hand-in-hand with mode substitution; that is, a mile of bicycling (and an accompanying substitution for a nearer destination) may replace a much longer automobile trip, thereby increasing the extent of the substitution effect to greater than a 1:1 relationship. However, a single automobile trip could be replaced by more than one AT trip (as was found by **Handy and Clifton (2001)**), in which case the substitution effect is less than 1:1.

Time horizon

The most elusive dimension of substitution relates to the time horizon over which the effect takes place. Two disparate examples illustrate this point. Consider an individual who drives for most trips but decides to cycle to work on a pleasant spring day; his "default setting" is driving, and any AT could be considered substitution. At the other extreme is an individual who chooses to live in a location close to her work so that she does not need to own a car; she walks, cycles, or uses transit for almost all trips, having made this a lifestyle decision. In the latter example, it is difficult to assign a specific substitution rate; *all* trips are substituting for driving in some sense, though over the long-term rather than as a result of a daily substitution decision.

Activity patterns

Mode substitution can lead to other changes in an individual's activity patterns, which might lead to secondary changes in travel behavior. For instance, walking or bicycling instead of driving to work might provide enough exercise that it leads to a reduction in driving trips to the gym, thereby extending the reduction in driving beyond the initial substituted trip. Alternately, using telecommunications to carry out an activity rather than driving to a destination. In this case, saving time that could hypothetically be spent on an activity that necessitates an automobile trip that would not have otherwise occurred (**Krizek et al., 2009a**).

Literature review

There is a dearth of conceptual and empirical literature addressing the ability of walking and bicycling to substitute for driving. Existing literature identifies the significance of substitution behavior but does not adequately address the myriad conceptual and methodological issues regarding AT substitution. Relevant research offers two directions for empirical analysis of substitution behavior: (i) indirect inference and (ii) direct questioning. First, it is important to distinguish existing literature on substitution between identifying substitution potential and quantifying existing substitution behavior.

AT substitution is increasingly relevant because of the significance of the claims that depend on it. For example, New Urbanist doctrine has long held that higher density, mixed-use development spurs increased levels of AT and transit use, with a concomitant decline in auto travel (**Calthorpe, 1993**). Recently, several reports and other publications have estimated various benefits of walking and bicycling based on the share of vehicular travel that could be replaced by AT. The California Department of Public Health (CDPH) applied its Integrated-Transport and Health Impacts Model (I-THIM) to illustrate impacts of long-term AT substitution scenarios. The most ambitious scenario modeled for the San Francisco Bay Area predicts a 45% reduction in GHG emissions and 2236 fewer deaths and 22,807 years of life gained by 2035 (**CDPH, 2011**). **Grabow et al. (2012)** estimate AT substitution scenarios in terms of environmental impacts (as particulate matter reductions) if *all* round-trips under eight kilometers by on-road light-duty vehicles were replaced by AT. Substitution potential scenarios yield estimated savings as high as $4247.5 million. **Gotschi and Mills (2008)** also assign high monetary values to AT substitution, using scenarios based on the fact that roughly half of all trips in the US are three miles or less, a feasible distance for AT modes, as a basis for its analysis (**Table 1**). They conclude that impacts of AT substitution in the US could be as high as $65 billion annually.

The above examples each begin with a known number of driving trips and then estimate or assume what fraction of those trips *could be* replaced by AT – an assumption of substitution potential. Such assumptions lack an empirical foundation and may or may not be realistic for the particular context.

Researchers currently lack a credible evidence base to inform estimation values for substitution potential. Our literature review yielded a limited number of studies quantifying substitution, the majority of which infer substitution from revealed behavior (i.e., "indirectly inferring" substitution). This category includes statistical analysis of individual-level travel data, frequently comparing travel behavior across communities with differences in urban form. An alternative approach is to directly ask respondents about substitution for a recent trip (i.e., "direct questioning"). Either approach—indirect inference or direct questioning—could rely on probabilistic or non-probability samples, depending on intended generalizability. Both indirect inference and direct questioning could be applied to either type of substitution: share of driving trips replaced by AT, or share of AT trips replacing driving. Note that most studies focus on the dimensions of mode and trip type as these tend to be the most straightforward to identify and measure. The two approaches and accompanying methodologies are discussed below.

Indirect inference

Studies employing indirect inference of substitution through population-based surveys test the degree to which communities with higher levels of neighborhood access have different mode share (a coarse indicator of substitution) than others with lower neighborhood access. Such an approach has been criticized as it is unable to account for AT as anything other than substitutive (**Guo et al., 2007**); that is, a 1:1 trip substitution rate between AT and driving is assumed, which may over-estimate actual substitution (**Handy and Clifton, 2001**). For example, **Cervero and Radisch (1996)**, **Khattak and Rodriguez (2005)** and **Larco et al. (2012)** compared travel behavior across neighborhoods using data from limited surveys (i.e., rather than comprehensive travel diaries). Each study found higher walking shares and lower driving shares in pedestrian-friendly environments. Concluding that the difference reflected substitution and implicitly assuming that each additional AT trip substituted for a driving trip.

Greenwald (2003) aimed to improve on indirect inference by developing models of substitution rates for walking and transit (both relative to driving) for three nonwork trip types. He found that the substitution of walking trips for driving trips was more likely in areas with smaller lot sizes, more intersections, and greater mixing of land uses. Estimated substitution rates were then incorporated into mode split models, showing increased walking mode split where substitution was more likely. **Guo et al. (2007)** used travel diary survey data to jointly analyze trip frequency by mode, finding that greater concentrations of businesses, AT infrastructure, and street network connectivity were associated with increased AT use but not with changes in driving. Both studies rely on observed behavior to infer substitution but include a number of statistical controls through individual-level analysis, and both demonstrate that substitution is not 1:1.

Indirect inference has also been applied in studying the potential of information and communications technologies (ICT) to substitute for vehicle trips. A typology of ICT interactions with transportation, first described in the 1980s (**Salomon, 1985, 1986**), provided the basis for the empirical work on substitution effects that followed (**Krizek et al., 2009a**). **Bhat et al. (2003)** found any impact of ICT's on "non-maintenance" shopping activities to be mediated by a variety of individual factors. **Choo and Mokhtarian (2007)**, showed that ICT's impact on substitution is likely minimal and that ICT might in some cases actually induce additional trips.

Approaches using indirect inference are limited because they rely on comparisons between individuals or communities to infer

Table 1. Purported benefits of substituting AT for car travel.

Benefit	Status Quo[a]	Modest scenario[b]	Substantial scenario[c]
Avoided driving (billion miles per year) 23	69	199	
Fuel savings (billion gallon per year)	1.4	3.8	10.3
CO_2 Emission reductions (million tons per year)	12	33	91
Physical activity (average daily minutes per person)	3	5	9
Monetary value of above ($ billion per year)	4.1	10.4	65.9

Source: **Gotschi and Mills, 2008.**
a. The "status quo" scenario assumes that 9.6% of all trips in the US under 3 miles would be completed by walking or cycling.
b. The "modest scenario" assumes 13% of all trips in the US under 3 miles would be completed by walking or cycling.
c. The "substantial scenario" assumes 25% of all trips in the US under 3 miles would be completed by walking or cycling.

substitution; and they tend to infer 1:1 substitution rates. The approach *could be* effective in isolating dimensions of substitution beyond mode and trip type. For example, an aggregate approach may be more effective in identifying long-term substitution than the direct questioning approach described below.

Direct questioning

Direct questioning employs surveys to ask respondents to report the mode they used for particular trips and to speculate on what mode they would have chosen had the chosen mode not been available (i.e., a counterfactual). Responses are then aggregated to estimate AT trips that substitute for driving. The direct questioning approach has been used to study both ICT and AT substitution effects.

Handy and Yantis (1997) surveyed individuals regarding recent purchases from a catalog, movie rentals, or phone-banking. Respondents speculated on alternative shopping behavior. Approximately half of movie-goers stated they would have stayed home if they had access to the same movies that were currently in the theater, home shoppers reported that 20% of purchases (either online or from televised shopping channels) replaced a trip to the store. Substitution rates for online or phone banking varied from 46% to 21%. It is possible that, given increased internet access and use since this study was conducted, substitution rates are higher today, but likely still well below a 1:1 substitution rate.

Krizek et al. (2009a) applied a direct-questioning approach, finding 27% of survey respondents willing to substitute travel to the bank for ICT (but less than 20% willing to substitute ICT for other non-work travel). Logistic regression suggested an increased likelihood of substitution among younger, educated individuals with Internet access. In terms of the dimensions of substitution, these findings shed light on the individual characteristics impacting mode of substitution by trip type.

More germane to AT, **Handy and Clifton (2001)** used household surveys to examine substitution for non-work trips, finding that increased walking and local shopping may lead to fewer and shorter car trips. The survey asked respondents to recall their last walking trip to a store and speculate on alternative travel options. Results indicated that nearly two-thirds of walking trips to the store substituted for driving trips, but that a substantial share were induced walking trips. In turn suggesting that assuming every utilitarian walking trip replaces a driving trip overestimates vehicle substitution.

The direct questioning approach does not rely on assumed substitution rates, thereby potentially providing a more accurate measure of substitution. Substitution behavior is identified for specific trip types and modes, without relying on assumptions or mode choice models. This approach can therefore help distinguish between induced AT and vehicle substitution. Direct questioning requires individuals to consider a counterfactual scenario; if the "last trip" was some time ago, the thinking may difficult. Furthermore, as AT is often considered a "virtuous behavior" that many people feel they should be engaging in more frequently (**Krizek et al., 2009b**), they may overestimate their behavior. Existing examples of direct questioning, have found substitution rates considerably less than 1:1.

Data collection

Substitution is a complex phenomenon, and addressing its many dimensions is challenging. The most appropriate approach for a specific study depends on the goals of that study, the need for scientific rigor, and the feasibility of the different possible approaches. In this study, we devised and implemented an intercept survey method that directly measures AT substitution at the individual level. This effort aimed to achieve two objectives: first, to pilot test the feasibility of a short, simple survey for practitioners; second, to explore actual AT substitution and contribute to the limited literature on the topic. Given the small number of survey locations (described) below, results are not generalizable but do provide direction for further research.

Relative to existing approaches, our effort stands out in three important ways. First, the majority of prior studies focus on walking; we focus on bicycling as well. Second, existing direct questioning approaches use probabilistic samples and household surveys; we use an intercept survey. An intercept survey is advantageous because it is affordable, simple, and easy to administer. Third, intercepting travelers may provide more accurate measurements of substitution because respondents are speculating on the trip they are currently making, rather than recalling past travel.

Our approach focuses on the two most straightforward dimensions of substitution, trip type and mode. We initially aimed to address additional dimensions of substitution but concluded that the direct questioning approach with an intercept survey was not well suited for this purpose. Our results highlight the importance of developing complementary methods for addressing the extent, time horizon, and activity participation dimensions of substitution in future studies.

For the pilot study, we chose two metro areas, Denver, Colorado, and Sacramento, California. Specific locations in three cities within the greater Denver metro area (Colorado) were surveyed: Denver, Boulder, and Littleton (see **Fig. 1**). Locations in two cities within the Sacramento metro area (California) were surveyed: Sacramento and Davis. These locations were selected because they contained a range of built environments and community types. Furthermore, they represented a spectrum of downtown urban centers and outlying suburban neighborhoods (**Fig. 2**).

Specific sites in downtown, suburban, and small/college towns were chosen to: (a) capture both pedestrians and cyclists, (b) capture utilitarian trip purposes (in addition to recreational trip purposes), (c) intercept travelers at natural stopping, slowing, or converging points. Sites were typically at intersections between dedicated AT facilities and road crossings, as they attracted higher volumes of AT users. There is little consistency in AT facilities across metro areas, making comparable site selection challenging and that is reflected in widely variable response rates. Photographs of "typical" downtown, small/college town, and suburban survey locations are provided (**Fig. 3**), and **Table 2** provides details on the survey sites and rates each site's suitability for AT intercept surveys. Description and commentary are intended to provide directions for improving future AT intercept survey methodology.

Bicyclists and pedestrians passing through the selected sites were surveyed during two-hour periods (between 4:30 and 6:30 pm) in August and September of 2009. A single administrator wore a t-shirt designating his or her affiliation as a member of the university research team and signage notified travelers that the survey was being conducted; small incentives (e.g., coupons, nutrition bars, water bottles) were provided. Survey administrators systematically approached every third passerby (after completing the previous survey). Thus, the sample approximates a random sample of the population of AT users at each site (as opposed to a random sample of all AT users).

Participants were queried regarding whether their current trip was recreational or utilitarian. If the latter, respondents were then asked, "What would you have done if you hadn't walked (or cycled) for this trip?" (the substitution question). We provided fixed responses (e.g., driven, used transit, would not have made the trip at all, would have made the trip a later time, combined it with other travel) and also invited open comments.

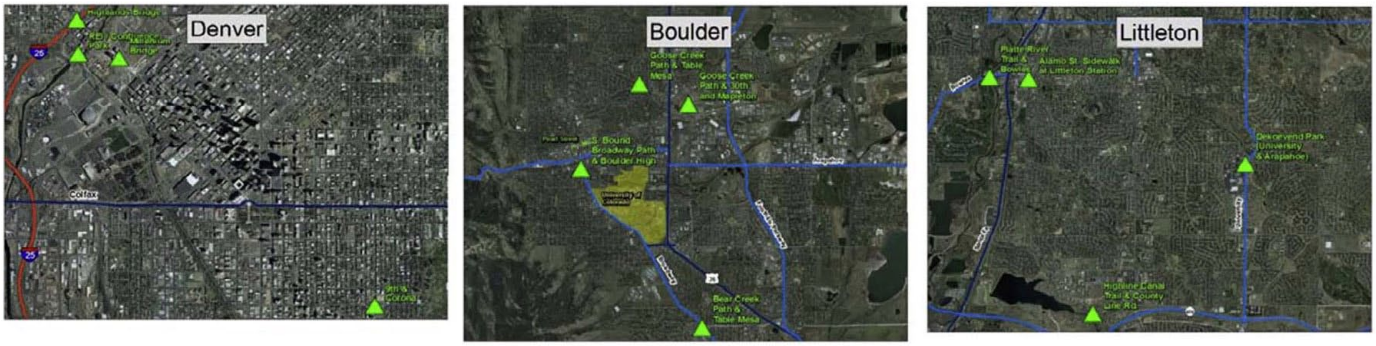

Fig. 1. Denver Metro Area Survey Sites (including individual survey administration locations within each metro area community).

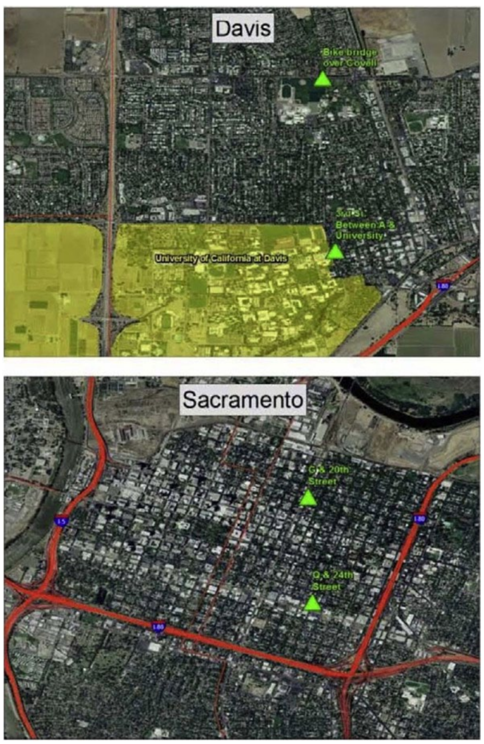

Fig. 2. Sacramento Metro Area Survey Sites (including individual survey administration locations within each metro area community).

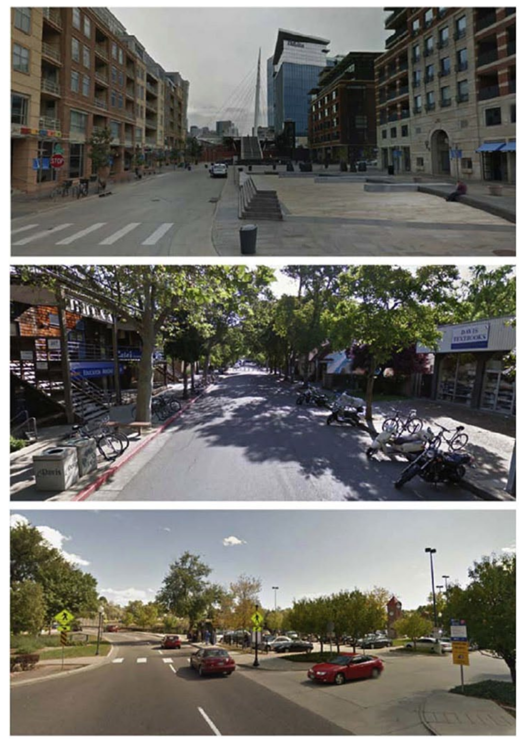

Fig. 3. Selected images of each type of survey location. Top: Downtown location (Millennium Bridge; Denver, CO). Middle: Small/College town location (3rd Street and University Avenue; Davis, CA). Bottom: Suburban location (W. Alamo Avenue at Littleton Station; Littleton, CO). Photo credit: Google Street View.

Survey results and analysis

Descriptive statistics

Across all of the survey sites, 729 people were approached and 311 agreed to complete the survey, yielding a 42% response rate. Summary statistics of survey respondents and utilitarian AT users are presented in **Tables 3 and 4**, respectively. The majority of respondents were in their early-mid 30s, and about two-thirds were male. We attribute relatively low response rates – particularly in Sacramento – to a poor choice of administration sites for an intercept survey of this type (see **Table 2** and Discussion section for a detailed discussion of this issue).

Survey locations have been designated as "ideal," "suitable," and "unsuitable." Ideal survey locations included high levels of AT travel and natural slowing or stopping points so that surveyors could easily approach travelers. There is a dearth of AT traffic volume data at both the local and national level in the US (**Lindsey et al., 2014**); our survey cities were no exception. In the absence of local AT counts (or similar) data, survey administration sites were selected based on local knowledge by members of the research team. In practice, multiple sites proved suitable if the site either evidenced high levels of AT travel or included natural slowing/ stopping points for users. Unsuitable sites lacked significant AT use or natural stopping points (despite existing high quality bike/ped infrastructure).

To better detect possible non-response bias, gender, mode (bicycle or walking), and attire (business clothing, casual clothing, or exercise clothing) of non-respondents was recorded. **Table 5** illustrates that the gender split is similar for respondents

Table 2. Description of intercept survey sites.

Metro area and city		Survey sites	Walk score[a]	Intersection density (per square mile)[a]	Average block length (feet)[a]	Location type	Description	Comment
Denver, CO metro area sites	Denver	Confluence park	89	94	502	Downtown	Bike/ped trail junction and shopping center with nearby bike parking	Ideal site: Destination for high levels of bike/ped traffic
		Millennium bridge	94	109	502	Downtown	Downtown bike/ped bridge	Suitable site: Lacking natural stopping point
		Highlands bridge	86	117	499	Downtown	Downtown bike/ped bridge	Suitable site: Lacking natural stopping point
		9th Avenue and Corona	89	144	459	Downtown	Mixed-use location with nearby bike parking	Ideal site: Destination for high levels of bike/ped traffic
	Boulder	Broadway path at Boulder high school	91	180	348	Small/ college	Natural bend in a bike/ped trail	Suitable site: Lacking natural stopping point
		Goose Creek path at Edgewood Drive	69	148	420	Small/ college	Bike/ped trail and street intersection	Suitable site: Lacking natural stopping point
		Bear Creek path at Table Mesa Drive	83	150	512	Small/ college	Bike/ped trail and street intersection	Suitable site: Lacking natural stopping point
		Goose Creek path at 30th Street and Mapleton	85	127	453	Small/ college	Bike/ped trail and street intersection	Unsuitable site: Path users approached from multiple directions at speed
	Littleton	Dekoevend Park	66	97	541	Suburban	Bike/ped trail and neighborhood park	Suitable site: Low bike/ped traffic volumes
		Platte River trail at Bowles Place	68	107	492	Suburban	Bike/ped trail and street intersection	Suitable site: Few utilitarian AT users (mostly cyclists)
		W. Alamo Avenue at Littleton downtown station	86	124	476	Suburban	Intersection of bike/ped trail with transit (bus and light rail)	Unsuitable site: Few utilitarian AT users (mostly pedestrians and transit users)
		Highline Canal trail at County Line Road	46	43	679	Suburban	Bike/ped trail intersection	Suitable site: Low bike/ped traffic volumes
Sacramento, CA metro area sites	Davis	Bicycle Bridge at Covell Boulevard	45	73	522	Small/ college	Bike/ped bridge in residential area	Suitable site: Lacking natural stopping point
		3rd Street and University Avenue	98	127	472	Small/ college	Primary entrance to university campus from downtown	Ideal site: High volume of AT users and natural stopping point
	Sacramento	G Street and 20th Street	95	153	413	Downtown	4-way intersection in mixed-use area with bike lanes and sidewalks	Unsuitable site: Low bike/ped traffic volumes
		Q Street and 24th Street	88	172	400	Downtown	4-way intersection in mixed-use area with bike lanes and sidewalks	Unsuitable site: Low bicycle traffic volumes

a. Source: Walkscore.com

Table 3. Descriptive statistics – survey respondents.

Location – full sample (n = 311)	Walking (n = 114)		Cycling (n = 197)		Total	
	Recreational	Utilitarian	Recreational	Utilitarian	Recreational	Utilitarian
Littleton, Colorado	14	10	22	19	36	29
Boulder, Colorado	7	2	18	57	25	59
Denver, Colorado	10	28	10	28	20	56
Davis, California	20	16	17	19	37	37
Sacramento, California	1	6	2	5	4	11
All locations	52	62	69	128	121	190

and non-respondents. However, a slightly higher rate of cyclists chose not to respond to the survey; after consulting with survey administrators, we concluded that this is likely attributable to the difficulty in stopping faster moving travelers.

Responses to the "substitution question" (**Fig. 4**) form the foundation for the analysis of substitution impacts attributable to AT. Those who said their AT trip substituted for a driving trip were typically male, somewhat younger than the total respondent pool, and most frequently cyclists wearing helmets. Respondents who said that they would have driven had they not been able to walk or bicycle for that trip ranged from a low of 23.7% in Denver to a high of 72.4% in Littleton (**Table 6**). In most locations, less than half of AT trips substituted for driving. Note that these substitution values are for respondents engaged in utilitarian travel (rather than recreational). Depending on the community, the responses for "would have used light rail or bus" surpassed "would have driven." **Table 6** compares characteristics of travelers whose trips substituted for driving versus those that substituted for other options. Characteristics are fairly similar across the two; notable differences exist for helmet use (72% of substitutors vs. 44% of non-substitutors) and the percent holding a bus pass (29% of substitutors vs. 43% of non-substitutors).

Table 4. Descriptive statistics – utilitarian AT users.

Utilitarian travelers – all locations (n = 190)	Utilitarian walking (n = 62) Mean	SD	Utilitarian cycling (n = 128) Mean	SD	Variable description
Auto substitution trip	0.263	0.444	0.508	0.501	Binary: 0 = Would have done other (i.e., transit, walk/bike, or stayed home); 1 = Would have driven
AT trips/week	10.460	11.345	9.566	7.543	Numeric (self-reported)
Access to a car	0.820	0.500	0.883	0.322	Binary: 0 = No; 1 = Yes
Car trips/week	4.188	3.337	4.069	4.016	Numeric (self-reported)
Number of children residing in household	0.387	0.856	0.516	0.851	Numeric
Number of adults residing in household	2.113	1.380	2.219	0.987	Numeric
Possess a bus pass	0.361	0.484	0.391	0.489	Binary: 0 = No; 1 = Yes
Age range	3.08	1.245	3.08	1.070	Ordered Categorical: 1 = <20 years; 2 = 20–30 years; 3 = 30–40 years; 4 = 40–50 years; 5 = 50–60 years; 6 = >60
Wearing a helmet	n/a	n/a	0.619	0.487	Binary: 0 = No; 1 = Yes
Gender	0.613	0.491	0.719	0.451	Binary: 0 = Female; 1 = Male

Table 5. Descriptive statistics – survey respondents versus non-respondents.

	Respondents (n = 311)		Non-respondents (n = 418)	
Gender	Female 104	Male 207	Female 139	Male 279
Mode	Walk 197	Bicycle 114	Walk 199	Bicycle 219

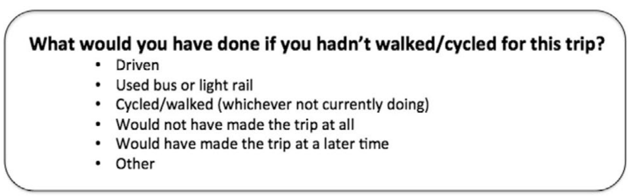

Fig. 4. Substitution question.

Logistic regression

Recognizing that we have a modest and non-representative sample owing to the "proof-of-concept" nature of the pilot intercept survey, we employed logistic regression to explore the factors that impact the likelihood that a particular AT trip is substituting for an automobile trip, using the following general formulation:

$$\log \frac{\Pr(Y = \textit{AT substitution Trip})}{\Pr(Y = \textit{Non AT substitution Trip})} = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots \beta_k X_k$$

The binary logistic regression model (presented below) estimates the probability (Pr) that an AT trip is substituting for a vehicle trip (the dependent variable (y)), where $y = 1$ indicates the response "I would have driven [if I hadn't walked/biked for this trip]" and $y = 0$ indicates a response other than "I would have driven." Two binary logit models are reported herein, a bicycle substitution model and a walking substitution model.

The initial logit model formulation (the "global" model) included walkers and bicyclists and all possible covariates in the dataset. Because of a large standard error for mode of traveler (walk or bicycle), we split the sample into walkers and bicyclists and ran two separate regressions. Due to sample size concerns, each model was reduced using a systematic manual stepwise process (detailed in **Table 7**). Final model formulations are as follows:

Bicycle Binary Logit Model:

$$\log \frac{\Pr(Y = \textit{Bicycle Substitution Trip})}{\Pr(Y = \textit{Non Substitution Trip})} = \alpha + \beta_1 \textit{WeeklyCarTrips}1 + \beta_2 \textit{BusPass}2 + \beta_3 \textit{Helmet}_3$$

Walking Binary Logit Model:

$$\log \frac{\Pr(Y = \textit{Walks Substitution Trip})}{\Pr(Y = \textit{Non Substitution Trip})} = \alpha + \beta_1 \textit{WeeklyCarTrips}_1 + \beta_2 \textit{Age}_2 + \beta_3 \textit{Gender}_3$$

The literature does not offer explicit guidelines for recommended minimum ratio of observations-to-predictors; however, numerous sources suggest a minimum 10–1 (observations to predictors) ratio (**Peng et al., 2002**) and each model exceeds this recommended ratio. Details of stepwise model-fitting process and final model formulations are specified in **Table 5**. Results should be interpreted cautiously given the exploratory nature of the data collection, non-representative sample, and modest sample sizes in the regression models.

The logit models for walking substitution and bicycling substitution point to the inherent complexity of substitution behavior. The models for walking versus bicycling fail to share any significant variables at $p < 0.05$ significance level; however, number of car trips per week is significant in both models at $p < 0.1$ significance level. Age of survey respondent is the sole significant predictor (at $p < 0.05$) in the walking model, indicating that with each unit increase in age, and controlling for all other variables in the model, the odds that individuals are substituting an auto trip are 1.99 times higher. Similarly, car trips per week are associated with 1.22 times greater odds that the current walking trip is substitutive (but this variable is only significant at $p < 0.1$), when holding all other variables constant. While not strongly significant, the model suggests that women are less likely to report that their current walking trip substitutes for auto travel.

The bicycling model indicates that number of car trips per week and wearing a helmet are significantly (at $p < 0.05$) associated with the likelihood of a substitutive bicycle trip, while possession of a bus pass is significant at $p < 0.1$ level. After controlling for all other variables in the model, as weekly car trips increase, a respondent has 1.19 times to the odds of reporting that they "would have driven" for a particular bicycle trip. Similarly, wearing a helmet is significant and positively associated with substitution travel; for respondents wearing a helmet, the odds of reporting bicycle substitution are 2.512 times the odds

Table 6. Substitution responses and characteristics of substitution vs. non-substitution travelers.

Responses to: What would you done if you hadn't walked/biked for this trip?

Location	Driven	Used bus or light rail	Cycled/walked (whichever not currently doing)	Would not have made the trip at all	Would have made the trip at a later time	Other	Total
Denver	23.7%	32.2%	20.5%	18.6%	–	5%	100%
Boulder	57.1%	30.3%	9%	3.6%	–	–	100%
Littleton	72.4%	17.3%	–	–	6.8%	3.5%	100%
Davis	25%	8.3%	47.2%	11.2%	–	8.3%	100%
Sacramento	27.3%	45.4%	9.1%	–	9.1%	9.1%	100%

Characteristics of substitution versus non-substitution travel (entire sample across all sites as a percentage of utilitarian travel (non-recreational)

	Substitution trip (e.g., I would have driven)	Not a substitution trip (e.g., I would have used light rail, not made trip at all, made a trip at a later time, combined it with other travel)
Median age (years)	35%	30%
Female	35%	33%
Male	65%	67%
Walk	24%	43%
Bicycle	75%	57%
Wearing helmet (as% of cyclists)	72%	44%
Self-reported non-motorized trips/week (mean)	8.7%	11.2%
Access to a car	97%	75%
Possess a bus pass	29%	43%

Table 7. Binary logistic regression bicycle substitution model, walking substitution model.

Bicycle substitution	Coefficient	Standard error	Odds ratio	*p*
Constant	1.010	0.405	0.435	0.040
Car trips/week	0.174	0.074	1.190	0.019
Possess a bus pass	_0.799	0.414	0.450	0.054
Wearing a helmet	0.921	0.434	2.512	0.034

- n = 118
- Cox and snell R^2 = 0.155
- Nagelkerke R^2 = 0.206
- Chi-square = 19.836, df = 3 ($p < 0.000$)
- Variance Inflation Factor (VIF) < 1.2 for all covariates in model
- Initial model formulation: AT trips per week, Car trips per week, Number of children at home, Number of adults at home, Possess a bus pass, Age, Wearing a helmet, Gender.

Walking substitution	Coefficient	Standard error	Odds ratio	*p*
Constant	_3.457	1.258	0.032	0.006
Car trips/week	0.206	0.115	1.229	0.073
Age	0.692	0.301	1.998	0.022
Gender	_1.201	0.743	0.301	0.106

- n = 52
- Cox and snell R^2 = 0.182
- Nagelkerke R^2 = 0.260
- Chi-square = 10.438, df = 3 ($p < 0.01$)
- Variance Inflation Factor (VIF) < 1.1 for all covariates in model
- Initial model formulation: AT trips per week, Car trips per week, Number of children at home, Number of adults at home, Possess a bus pass, Age, Gender.

(1) Due to concerns regarding small sample sizes in the logit models, a systematic manual stepwise process was used to reduce the overall number of covariates. Only covariates significant at $p < 0.1$ were included in final model. The modest significance criterion provides a firm cut-point for model fit while recognizing the exploratory nature of the analysis. (2) The global logistic regression model (n = 192; Cox and Snell R^2 = 0.190; Chi-square = 24.813, df = 9 ($p < 0.003$) including all covariates detailed in "initial model formulation" yielded a single significant variable (possession of a bus pas p = 0.03). The standard error of the variable AT MODE (walk or bicycle) was extremely large (SE = 40193.110) suggesting the need for separate walk and bicycle models.

for respondents not wearing a helmet. In contrast, possessing a bus pass suggests a reduced likelihood of substitution travel. Implications of the findings from the walking and bicycling regression models are discussed in detail in the next section.

Discussion

This study offers a first attempt to develop a practical and robust approach to directly examine AT substitution behavior. Findings have both empirical and practical implications. Empirical findings include the results of the intercept survey and statistical analysis. Practical implications include directions for improving direct approaches to understanding AT travel behavior in general and AT substitution in particular.

Understanding AT substitution

Reported substitution rates varied widely across communities, and this variation may be due to a variety of underlying factors. For example, the substitution rates for Boulder (57.1%) and Davis (25%)—both well-known for their extensive bicycle infrastructure and high levels of utilitarian bicycling—present an interesting contrast and raise important issues about how to define substitution. The relatively low rate in Davis could imply that most bicycling trips, even those made to destinations rather than for recreation, are induced trips and therefore optional to some degree. Another possible interpretation is that bicycling for these Davis residents is so entrenched a habit that they may not consider driving, suggesting a long-term or more permanent substitution of bicycling for driving. Similarly, if residents of Davis have forgone owning a car because of the ease of bicycling, they would not report substitution on a particular trip, though they have in effect substituted bicycling for driving in the long-term. One of the limitations of the study is that we can neither confirm nor reject these possible interpretations; further work is needed to develop methods that can address this time horizon dimension of substitution.

The high rate of reported substitution in Littleton (72.4%) has several possible explanations. Littleton is a suburban area, and the survey was administered along a popular recreational trail system; respondents may have been combining an exercise trip with a shopping trip (which could be considered an induced trip if the shopping trip would not have been made otherwise). Another possible explanation is that because of the predominant urban form and lack of transit, the only other viable mode choice is the car. The former case would not be considered substitution, while both cases highlight the limitations of the survey instrument.

The substitution rates in Denver vary more than in the other locations. Given the abundance of transit services available in Denver, such variation could suggest that AT substitution comes at the cost of transit ridership (32.2% of respondents reported they would have taken transit), and other non-motorized modes (20.5% substitution for other AT), in addition to auto travel. The 18.6% rate of induced trips (i.e., trips that would not have been made otherwise) could also suggest health and economic benefits of increased bicycling and walking that is not substitutive.

The statistical analysis provides novel insights into the mode and trip type dimensions of substitution. Logistic regression models support the assertion that walking and bicycling substitution are distinct and sensitive to different factors. The analysis focused on auto substitution because of its relevance to GHG emissions and congestion. Regarding utilitarian travel, walk and bicycle substitution was significantly related to number of car trips per week. This relationship may be a function of either perceived or actual mode choice options: individuals who mostly drive may not have considered alternative options or may live and work in areas where driving is the most attractive option for most travel. The negative relationship between possession of a bus pass and auto substitution in the bicycle model indicates that AT substitution may vary as multi-modal options increase. AT may substitute for transit in communities with high transit ridership. Demographic characteristics do significantly impact travel behavior, but the relationship between such factors and AT substitution in particular has not been addressed previously. These findings may be valuable for refining predictive approaches to quantifying substitution potential (existing literature, described in the literature review section, does not account for demographic characteristics). The causal mechanisms underlying these findings remain unclear.

Helmet use among bicyclists is positively correlated with auto substitution. On one hand, this may reflect a "serious" commuter cyclist's conscious choice to forego auto travel; this conscious decision may correspond with an increased likelihood of reporting long-term substitution behavior as trip-specific substitution. On the other hand, it is unlikely that all cyclists who wear helmets are long-term bicycle commuters. New cyclists, trying out a new behavior and wearing a helmet due to safety concerns may claim trip-specific substitution but their uptake of a new behavior (and consequent longer-term substitution impacts) is missed by an intercept survey.

Empirical findings from the intercept survey provide initial insights into the specific factors impacting both walking and bicycling substitution for utilitarian travel; the mode and trip type dimensions of substitution. Analyses also provide directions for more robust approaches to understanding and quantifying the extent of and time horizon associated with substitution. The following section details proposed improvements to the piloted intercept survey that may better address additional dimensions of substitution.

Direct-questioning approach to at substitution: practical considerations

Reliably quantifying AT substitution is full of methodological and practical challenges. Any particular research design and analysis method has more or less ability to capture the different dimensions of substitution behavior. Indirect inference approaches are limited to comparisons of mode share. Direct questioning approaches rely on the ability of respondents to rapidly engage in complex reasoning. The "gold standard" of substitution study would likely consist of a longitudinal cohort study to address the complex dimensions of substitution, particularly extent, time horizon, and activity pattern, but such an approach is impractical for practitioners. To this end, we provide specific directions to improve AT intercept surveys for practitioners interested in understanding community-level AT substitution.

During the process of designing our survey instrument, we sided with parsimony on most accounts; we aimed not to overburden the respondent with caveats or possibilities, and thus did not address all dimensions of substitution. Our survey focused on mode and trip type, finding that with additional refinement, these two dimensions may be accurately quantifiable via direct-questioning:

- Survey Sites – **Table 2** describes some of the challenges in identifying appropriate sites for AT intercept surveys. Ideal locations require existing AT users and should incorporate a natural stopping or slowing point to give survey administrators the opportunity to approach travelers. To better control for destination (and by extension trip type), survey sites may be best placed at a destination when possible. As opposed to simply on/near existing AT infrastructure.
- Survey Questions – This study demonstrates that AT substitution varies by walking and cycling, availability of other mode choice options, and the social and built environment. Taken together, these issues suggest tailoring to community characteristics and research goals. For example, our exploratory analysis included multiple substitution options, but some communities may only be concerned with substitution for other modes. Survey questions should also be tailored to walkers and cyclists. The pilot survey treated these modes similarly, but findings revealed important distinctions. Demographic factors impacting walking substitution require further study. Social factors or unmeasured distinctions between types of cyclists should also be considered. There exist distinct typologies of cyclists (**Dill and Mcneil, 2013**), and it may be that our findings regarding helmet use and substitution reflect diversity within a demographically-similar population of cyclists. Finally, accurately quantifying trip-specific substitution requires accounting for both origin and destination; in addition to placing survey sites at clear destinations it may be advantageous for future research efforts to better account for such.

The strength of direct-questioning approach using an intercept survey is that it is an affordable and practical research method for understanding substitution by mode, trip type, and destination. Capturing the extent, time-horizon, and activity patterns associated with substitution may require longitudinal cohort studies or advanced computational simulations, and as such are impractical for most communities. With increased attention to AT mode (walker or cyclist), substitution mode of interest, and survey site selection, it is possible to adequately understand short-term substitution at the community level.

Conclusion

Communities are promoting walking and cycling and expect (either implicitly or explicitly) that AT comes at the expense of driving. Most assumptions about the substitution of AT for auto travel tend to overestimate the behavior, leading to unrealistic expectations of its ability to mitigate air pollution and decrease greenhouse gas emissions. This research informs the evidence base around environmental impacts of walking and bicycling. Environmental impacts may cumulatively be important, but our efforts suggest that accurately quantifying them is extremely challenging and results should be interpreted cautiously. Environmental benefits are just one justification of AT enhancements; other benefits to be included in a comprehensive evaluation include advances in health, livability, social interaction and economic conditions—all of which are *also* important aspects to consider in any robust analysis.

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